

# TEMPERATURE OF THE SOLAR CORONA FROM INTENSITY GRADIENTS MEASURED DURING THE MAY 30, 1965 TOTAL ECLIPSE\*

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A description is given of an experiment which consists of point-wise three-color photoelectric photometry of the solar corona. Persistent cloudy conditions before eclipse as well as thin clouds during the eclipse prevented attainment of the full original experimental objectives. However, the experimental techniques appeared to be entirely satisfactory, and the data obtained permit the determination of logarithmic intensity gradients which give a fairly reliable estimate for the temperature of the corona.  $T = 1.6 \times 10^6$  °K and  $T = 1.9 \times 10^6$  °K are found for the equatorial region with an inhomogeneous model and a mean atomic weight of 0.608 and 0.692, respectively, at a heliocentric distance of  $1.3 R_{\odot}$ .

## I. Experimental Aims

Photometry of the solar corona is often undertaken at total eclipses. Usually this takes the form of direct photographs which are calibrated; little photoelectric photometry is available in the literature although we should note the early photoelectric observations of the total coronal light by Stebbins and Whitford (1938). A recent exception is the work of Ney, Huch, Maas, and Thorness (1960); however, their primary interest was the polarization of the corona and, hence, their intensities were accurate only to 5%.

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Our aim was to do point-wise three-color photoelectric photometry from the center of the moon's disk to a projected distance of  $5 R_{\odot}$ . The colors would be chosen to cover as wide a wavelength range as practicable. No polarization measurements would be made with the equipment in an attempt to keep the experiment as simple as possible. The F corona would be eliminated using the known angular variation from the sun of this radiation and our observations at 4 to  $5 R_{\odot}$  which should be predominantly F corona. Scattered light in the atmosphere would be eliminated by our detailed knowledge of the light distribution over the lunar disk and theoretical calculations; observations of the sun and the solar aureole on a variety of days including the day of eclipse would be used to determine the scattering properties and optical thickness of the atmosphere as well as serving as an alternate, absolute calibration for the observations. Stellar observations were to have formed the primary absolute calibration.

Persistent cloudy weather vitiated many of the planned objectives, and the sun was seen through thin clouds at the time of the eclipse. However, the equipment appeared to function satisfactorily and the data obtained permit a determination of the logarithmic intensity gradient. The coronal equatorial temperature can be accurately determined from the logarithmic gradients, and hence, we discuss the experiment and the coronal temperature in this paper.

The areas of responsibility for this venture are: I (J.C.B.), basic conception of the experiment and data interpretation; II (W.C.L.), optics and photometer design; III (D.E.T.), design of mechanical control system and data-recording equipment. The experiment was performed by all three writers on the island of Bellingshausen, French Polynesia.

## II. Experimental Design

*Photometer and Optics* — Figure 1 indicates the optical system of the three-color photometer. The requirement of high spatial resolution meant that the colors would best be measured simultaneously, rather than sequentially with a color-wheel. In anticipation of the corrosive effects of the salt-laden atmosphere on Bellingshausen, plans were made to calibrate the photometric system on a daily

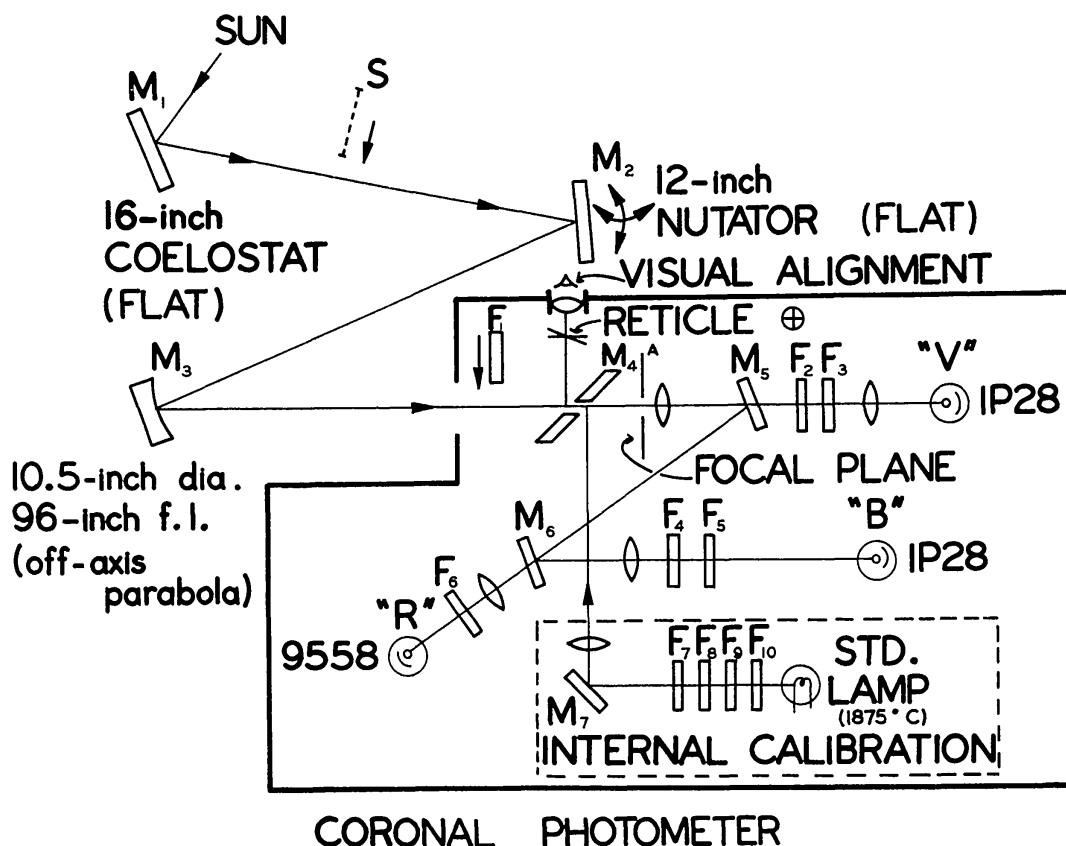


FIG. 1 — Schematic diagram of the optics and the coronal photometer; see the text for discussion.

basis both before and after the eclipse so that the effective color response could be arrived at accurately by interpolation; the plan was not executed because of clouds. This calibration was to be based on stars, supplemented by the sun, and so we chose the VBR (violet, blue, and red) system of Stebbins and Whitford (1943). The effective wavelengths of this system are 4130, 4850, and 6800 Å in response to a black body of 6000 °K. The telescope system involved three reflections with an off-axis parabola providing a 0.88-inch diameter solar image. At the focal plane is a circular aperture of 0.024-inch (corresponding to 50 arc-sec) diameter through which light passes to the photometer. Wavelength selectivity is by a combination of dichroic mirrors and colored glass filters plus the selective response of the different phototubes. Fabry lenses formed approximately 0.1-inch images of the parabola on the different photocathodes.

To view the sun for alignment and tracking tests, the light was attenuated  $10^{-6}$  by inserting a perforated screen S (transmission= $10^{-2}$ ) and a neutral density filter  $F_1$  (transmission= $10^{-4}$ ). The image could then be accurately centered by electric motion of the coelostat with reference to the reticle.

With the sun centered on the circular part of the reticle, light from the center of the disk passes through a hole in  $M_4$  and is of appropriate intensity for measurement by the B and R channels. (The filter  $F_1$  is almost opaque in the "V"). However, for reasons discussed by Stebbins and Kron (1957) in their paper on six-color photometry of the sun, this procedure (owing to the nature of the Fabry image) is unreliable, and observations of this kind were planned only as a possible supplement to the stellar data.

When  $M_4$  is "out," a star may be positioned on the cross-lines and photometered when the mirror is returned to "in." Also, when the mirror is "out," light from a standard lamp may be admitted to provide a partial calibration. The lamp source does not involve  $M_1M_2M_3$ , of course, and so cannot provide a complete calibration. But the lamp does provide a convenient reference for setting up the photomultiplier dynode voltages. The filter combination  $F_7 \dots F_{10}$ , determined by experiment, provided a close approximation to sunlight in spectral distribution.

*Electronics and Control* — The electronic equipment consisted of two major sections, a control section and a data-handling section. Both sections used digital techniques and circuitry almost exclusively.

The control section generated signals to cause the nutator to move so that the locus of its normal described a spiral of constantly increasing radius. At a certain terminal radius, the mirror returned to its initial position. Timing and control signals to the data-handling section were generated so the data could be digitized at the fastest rate possible within the limits imposed by the tape recorder.

The nutator was moved by pushing at two places  $90^\circ$  apart on the back of the mirror cell. The pushing arms consisted of screws rotated by stepping motors in fixed nuts.

If two pulse trains whose rates can be described by sine and cosine functions respectively were to be applied to these stepping

motors, the mirror would describe a circular scanning pattern. The technique for generating these signals consists essentially of the well-known technique (Korn and Korn 1956) of using two integrating devices to continuously generate the solution to the differential equation

$$\frac{d^2y}{dx^2} = -ky. \quad (1)$$

In this case the digital techniques employed in the digital differential analyzer (Huskey and Korn 1962) were used to approximate the performance of the analog devices discussed by Korn and Korn (1956). This was done to allow better and more precise control of the initial and final conditions and the scanning rates. To convert the circular scan to a spiral scan it was only necessary to multiply each of the output signals by a constantly increasing number. A complicating factor was the fact that as the spiral gets large, the stepping rate to the motors gets large as well. Therefore the rotation rate of the spiral was reduced as the spiral increased in size. Because the light intensity falls rapidly with increasing distance from the limb, the scanning pattern was altered to place most of the scans near the limb where the light is concentrated; some data were taken as far out as 5 solar radii from the center of the disk. The change in the scanning interval is shown in Figure 2 which is the track of a beam of light reflected onto a test film by the nutator. The scaling was such that 112 steps of the stepping motor moved the image one solar diameter.

It can be seen that the spiral is by no means a perfect one. Aside from the mechanical imperfections, this is due to the digital nature of the motion generation and to the error in generating the sine and cosine functions. These errors could be made much smaller if desired by using a longer word length, but since the only important thing is to know the precise location when data are taken, the word length used was very short, 10 bits and a sign. The X and Y counters which recorded the total number of pulses sent to the stepping motors were relied upon for accurate position information. The resulting scan and control unit, although complex, nevertheless was small enough to fit into a cabinet 17 inches wide by 8 inches high by 21 inches deep.

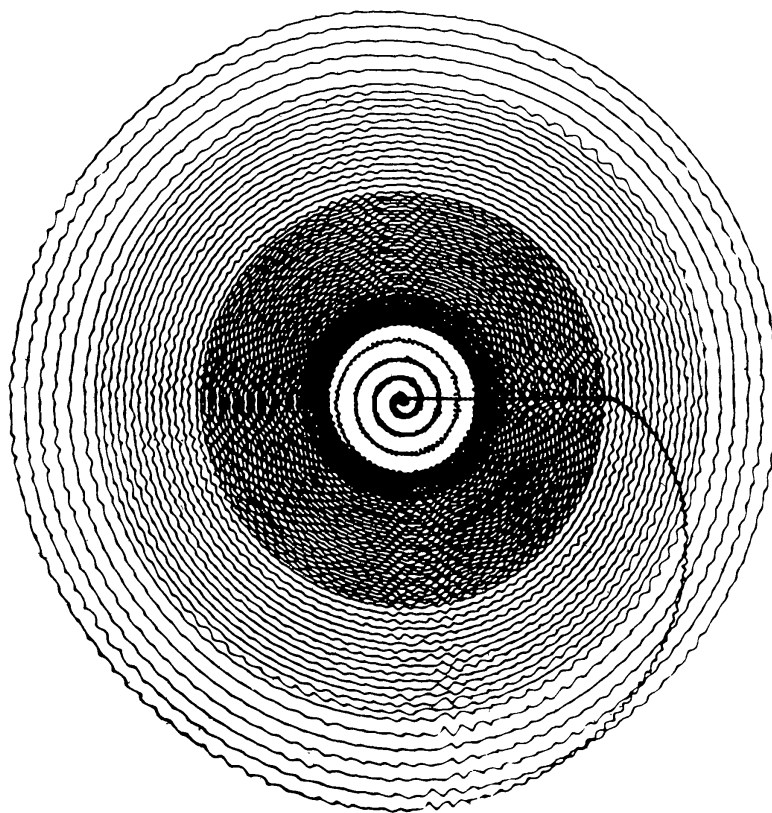


FIG. 2 — A test film of the scanning pattern. The outermost circle has a projected heliocentric distance of about  $5 R_{\odot}$ .

The data-handling unit was more conventional. The photocurrents were sent to photometer amplifiers with built-in time constants of 2.4 milliseconds. A control signal was sent to a sequencer unit approximately 400 times a second which caused the outputs of the three photometer amplifiers to be converted to a 14-bit number one at a time. This information, together with the values of the X and Y counters, was recorded digitally on a portable magnetic tape recorder. The entire electrical equipment block diagram is given in Figure 3.

The system accuracy can be described as follows: the quantizing error was about 0.02% at the peak intensity of the inner corona. Linearity was better than 0.1%. However, the greatest error was set by the limited number of photons detected per sample interval. This photon noise amounted to about 1% (rms) at peak coronal intensity.

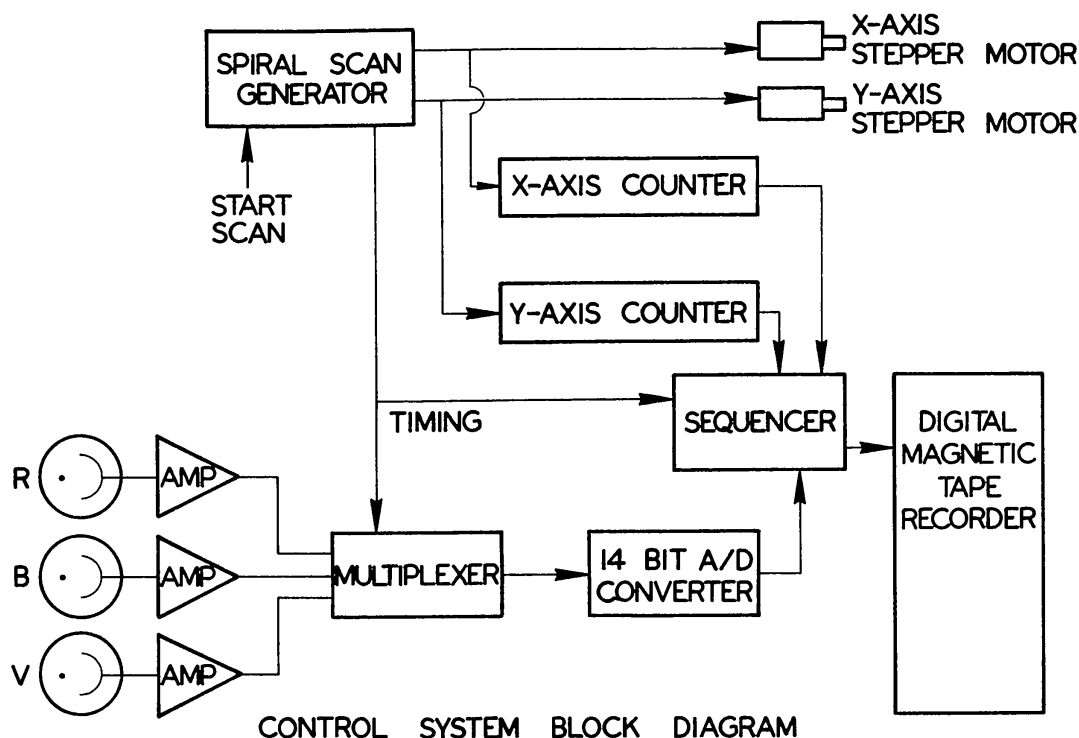


FIG. 3 — Schematic diagram of electrical equipment; see the text for discussion.

### III. Data Reduction

*Logarithmic Gradients* — Essentially two complete scans of the sun in three colors were obtained at the time of eclipse. Because of the lack of calibration and the thin clouds at the time of eclipse, it is not possible to seek details of coronal structure. Rather, we hope to use the advantages of a large number of points to produce two logarithmic intensity gradients — applicable to the solar equator and the polar region. While almost 80,000 points were observed, only a small fraction ( $\approx 8150$ ) were used in determining the logarithmic gradients (primarily because of the restriction in radial distance adopted below).

The following plotting procedure was adopted for the purpose of determining the average gradients. The disk of the sun was divided into 360 increments of  $1^\circ$  each. Within each  $1^\circ$  increment, the data points were sorted and ordered in terms of increasing  $\rho = r/R_\odot$ , the radial distance from the sun in units of the solar radius. The points for which  $0.65 \leq 1/\rho \leq 0.85$  ( $1.18 \lesssim \rho \lesssim 1.54$ ) were plotted on a  $1/\rho$  vs.  $\log I$  ( $I$ =intensity) graph, a plot being computed for each

color and each degree, making 1080 separate graphs for each of the two separate scans. The above limits for  $\rho$  were chosen because (1) for  $\rho \gtrsim 1.18$ , chromospheric effects seem negligible and (2) for  $\rho \lesssim 1.54$ , (a) the effect of the F corona is the least possible and (b) the value of the intensity  $I$  is large enough so that an error in the evaluation of the dark-sky intensity correction factor will not have an overwhelming effect on the slope of the graph  $1/\rho$  vs.  $\log I$ . For each plot, a least-squares fit is made, and the straight-line graph is extrapolated back to  $1/\rho = 0.85$ ; each graph is then individually normalized so that at  $1/\rho = 0.85$ ,  $\log I = 10.0$ . This means that each graph has been translated upwards along the  $y$  axis ( $\log I$ ) so that each least-squares fit begins at  $1/\rho = 0.85$ ,  $\log I = 10$ , and yet each fit retains its original slope. The  $1^\circ$  increment plots of normalized data points were then divided into four groups according to solar position angle. The groups are the north and south polar regions and the east and west equatorial regions; the solar latitude of  $\pm 70^\circ$  was chosen as the dividing line. For each of these regions, the normalized data points from each  $1^\circ$  increment were aggregated and superimposed on a single plot, giving four plots in each of three colors for each of the two scans. For each region, a least-squares fit was computed and plotted, and sample plots and fits for the equator and pole are shown in Figures 4 and 5. Grand means (by color) of the logarithmic gradient are given in Table I.

*The Coronal Temperature* — We compute the temperature of the corona on the basis of assumptions concerning the limb darkening, F corona, homogeneity, and mean molecular weight, but always on the assumption of an isothermal corona. The calculation amounts to a determination of  $d(\log_{10} I)/d(1/\rho)$  for the region of interest and a comparison with calculations made for different temperatures.

Before the comparison can be made, the F component of the observed (K+F) intensity must be eliminated. Because of the cloudy conditions, we have no direct knowledge concerning the ratio of F to K corona; however, the observed logarithmic gradient differs from the “standard model” for the equator at solar minimum given by van de Hulst (1953) by only 5%. Hence, we assume that the ratio of F to K corona is the same as on the model tabulated by van de Hulst (1953).

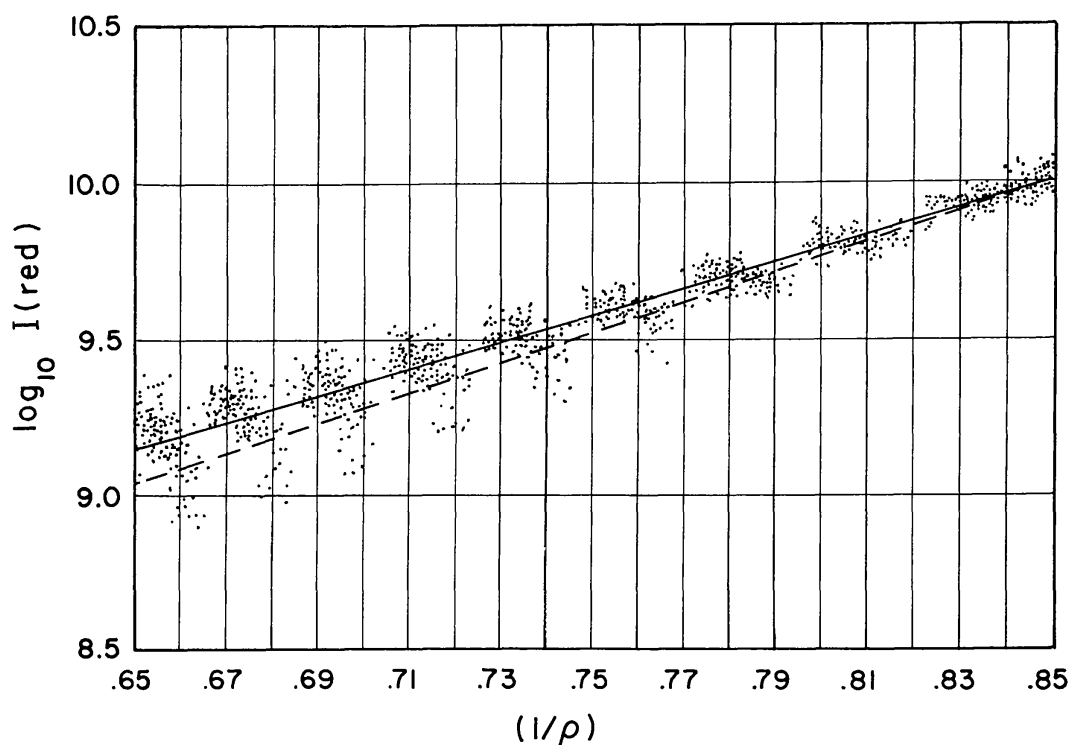


FIG. 4 — Sample determination of the logarithmic gradient for the observations in the red in one equatorial region on one scan. The solid line is the least-squares fit to the observed points; the dashed line gives the result after the subtraction of sunlight diffracted by interplanetary dust (F corona). The observed points show more concentration towards the solid line than indicated here; the denser concentrations have been thinned out to avoid overlapping. Four such graphs determine the gradients listed in Table I.

The calculation of  $\log I$  as a function of  $\rho$  with  $T$  as a parameter is entirely straightforward; see, for example, the summary given by Brandt and Hodge (1964, pp. 105–106, 110–111). Alternatively, it is a simple matter to compute the temperature  $T$  directly in terms of the measured  $d(\log_{10} I)/d(1/\rho)$ , neglecting the limb darkening, by writing out the integral for the intensity, taking logarithms, and differentiating. The result is

$$T = \frac{1.004 \times 10^7 Q(T/\mu) \mu}{\left[ \frac{d \log_{10} I}{d(1/\rho)} - \frac{\rho}{2.30} \right]} \quad (2)$$

where  $\rho$  = heliocentric distance in solar radii,  $\mu$  = mean atomic weight,  $I$  = intensity,  $T$  = temperature ( $^{\circ}\text{K}$ ), and

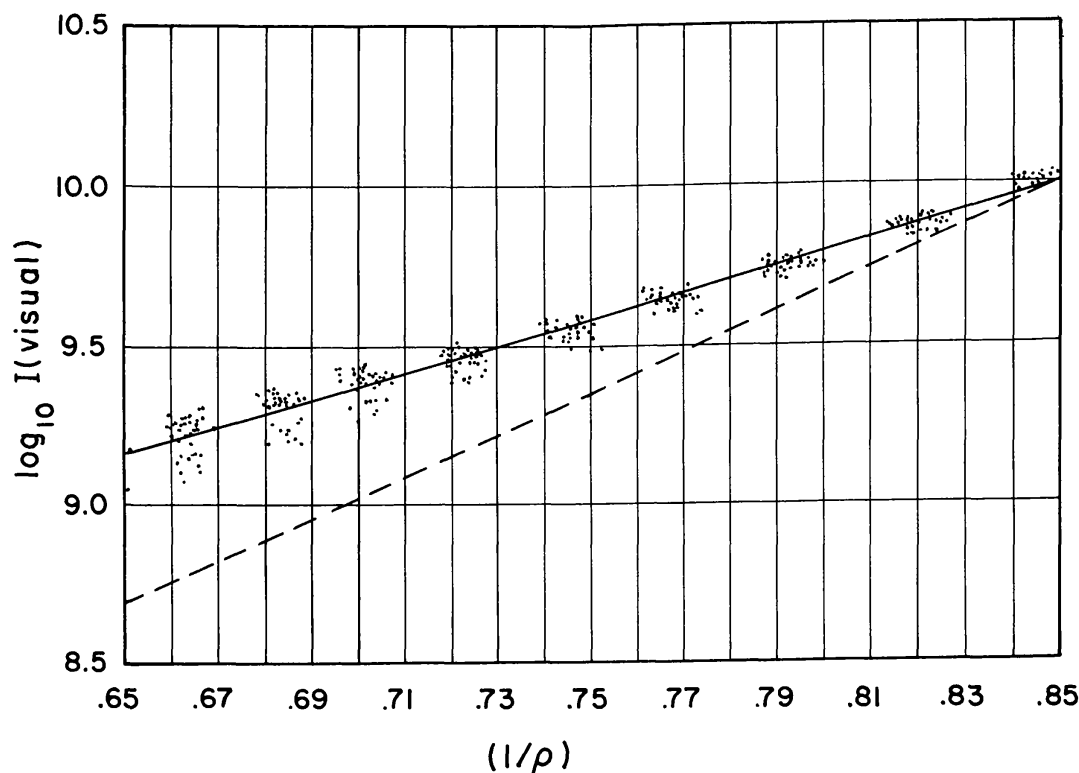


FIG. 5 — Sample determination of the logarithmic gradient for the observations in the visual of one polar region on one scan. The solid line is a least-squares fit to the points and the dashed line shows the (substantial) effect of the F-corona correction. Four such graphs determine the gradients listed in Table I.

$$Q = \frac{\int_0^{\pi/2} e^{[C \cos \theta / \rho]} \cos \theta \, d\theta}{\int_0^{\pi/2} e^{[C \cos \theta / \rho]} \, d\theta} . \quad (3)$$

Here,

$$C = \frac{G \mathcal{M}_\odot \mu m_H}{R_\odot k T} \quad (4)$$

where  $G$  = gravitational constant,  $\mathcal{M}_\odot$  = solar mass,  $m_H$  = mass of hydrogen atom,  $R_\odot$  = solar radius, and  $k$  = Boltzmann's constant. The function  $Q$  has been tabulated for  $\rho = 1.3$  and  $\mu = 0.608$  for a range of  $T$ , and it is found that  $Q = -0.049 [T/10^6] + 1.0013$  for  $[T/10^6]$  between 0.50 and 2.50. Hence, the two relations can be solved for  $T$  (with the  $\mu$  retained explicitly); in addition, the in-

TABLE I

## LOGARITHMIC GRADIENTS AND TEMPERATURES IN THE CORONA

Equator:

Color	$d \log_{10} I / d (1/\rho)$		$T (10^6 \text{ }^\circ\text{K})$		
	Observed	With F Corona Correction	Homo. $\mu = 0.608$	Inhomo. $\mu = 0.608$	Inhomo. $\mu = 0.692$
V	4.52	4.99	1.32	1.62	1.84
B	4.41	4.88	1.35	1.66	1.89
R	4.61	5.08	1.30	1.59	1.81

Pole:

Color	$d \log_{10} I / d (1/\rho)$		$T (10^6 \text{ }^\circ\text{K})$		
	Observed	With F Corona Correction	Homo. $\mu = 0.608$	Inhomo. $\mu = 0.608$	Inhomo. $\mu = 0.692$
V	4.27	6.59	0.99	1.14	1.30
B	4.45	6.87	0.94	1.09	1.24
R	4.34	6.77	0.96	1.11	1.26

clusion of limb darkening increases the deduced temperatures by 2%. Thus, the final expression is

$$T(\rho=1.3) = \frac{23.6\mu \times 10^6}{\left[ 2.30 \frac{d(\log_{10} I)}{d(1/\rho)} - 0.61 \right]}. \quad (5)$$

Note that the deduced temperature is directly proportional to the assumed mean atomic weight which we take to be in the range 0.608 to 0.692 for a completely ionized gas with relative composition of 10 hydrogen to 1 helium and 5 hydrogen to 1 helium, respectively. Note that  $Q$  is actually  $Q(\mu/\rho T)$  so that  $Q$  can be determined for other values of  $\rho$ , etc. from the specific tabulation given here.

The results are summarized in Table I; the effects of inhomogeneities have been included through the method given by Brandt, Michie, and Cassinelli (1965a).

#### IV. Discussion

The experiment discussed here appears to have functioned successfully. Future operation of the experiment under cloudless conditions should yield a large body of accurate, point-wise photoelectric coronal intensities. Even in operation under poor conditions, the logarithmic gradient and coronal temperature could be determined primarily because of the large number of points obtained.

The uncertainty in the equatorial temperature can reasonably be taken to be roughly the amount of the F corona correction. Then, the equatorial value of  $1.6\text{--}1.9 \times 10^6$  °K is uncertain by about 10–15%. For the same reason, the polar temperature is uncertain by some 30–35%. In addition, the polar determinations suffer from the lack of spherical symmetry and the difficulties in determining any polar electron densities as emphasized by Ney, Huch, Kellogg, Stein, and Gillett (1961).

These temperatures are in good agreement with the traditional determinations (e.g., van de Hulst 1950) and the recent detailed studies (Brandt, Michie, and Cassinelli 1965*b*). At least part of the observed temperature difference between the equator and the pole may be spurious; it has been pointed out (Brandt 1966) that the mean molecular weight may be substantially higher at the pole relative to the equator.

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